An intercomparison of water vapor measurements in the TTL and lower tropical stratosphere during AVE-WIIF, CRAVE and TC4: The importance and implications of laboratory calibrations with water vapor mixing ratios from 0-10 ppmv

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Introduction

1. Unexpectedly high relative humidities observed in the cold tropopause region in clear air and clouds challenge current microphysical and dehydration models.
2. The degree to which convective ice lofting and high supersaturations affect the stratospheric water vapor budget as our climate is changing must be resolved.

Accurate or "benchmark" quality water vapor measurements are needed:

- To address #1 above by constraining microphysical models required for understanding the evolution, lifetime, and dehydration potential of cirrus clouds in the TTL.
- To address #2 above and help resolve the importance of proposed strat-trop exchange mechanisms.
- To maintain an observational database for stratospheric trend measurements.
- To provide measurements in polar regions where heterogeneous ozone loss critically depends on ambient water vapor.
- For satellite validation.

Intercomparison of water vapor measurements in the UT/LS have highlighted systematic instrument differences:

- Water vapor measurements as summarized in Figure 1 of SPARC 2000 illustrated significant differences between water vapor measurements in the UT/LS.
- We focus on systematic differences observed between Harvard Lyman α, the balloon-borne NOAA CMDL Cryogenic Frost point Hygrometers (e.g. CMDL and CFH), and the Microwave Limb Sounder (MLS) on the Aura satellite. First intercomparison example shown here:

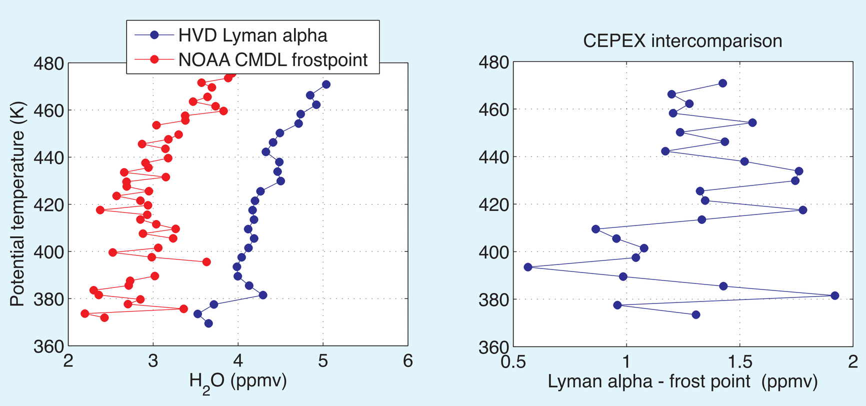

Figure 1. Intercomparison between Harvard Lyman α on the NASA ER2 and CMDL during CEPEX. Harvard points are binned and averaged at 2K intervals for data taken during aircraft dives at 2° S latitude on March 18, 21, 24, 29, 31 and April 4.

So how do we resolve this systematic difference?

Foundation for measurement accuracy must be laboratory calibrations tied to SI traceable standards.

Harvard calibrations

We illustrate the Lyman alpha calibration setup in Figure 2.

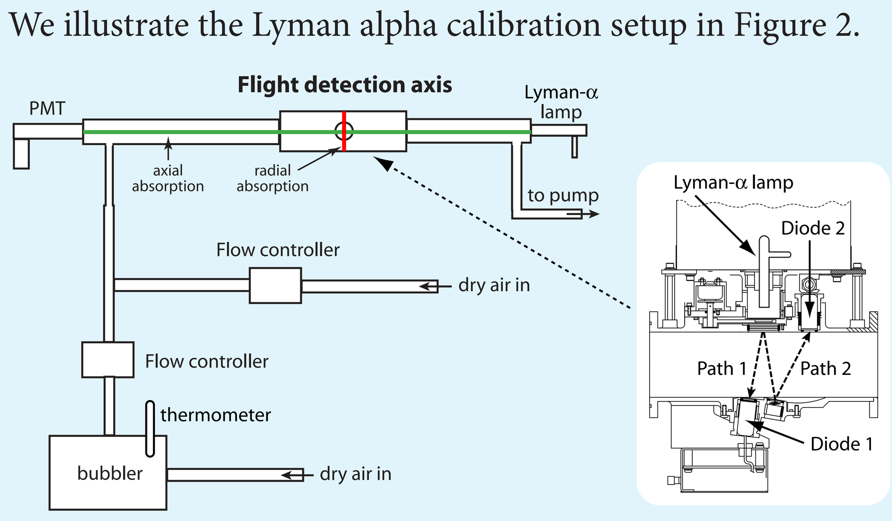

Figure 2. Schematic of the Lyman alpha calibration system (left); Lyman alpha detection axis (right); PMT (not shown) perpendicular to the air flow and lamp flux.

CONCLUSION: Instrument sensitivity in laboratory tied to physical and chemical properties of water.

However, systematic differences illustrated in Figures 1 and 7, and a CRAVE water vapor workshop report suggested the need for low water calibrations and intercomparisons, examples of which we show in Figure 3 below.

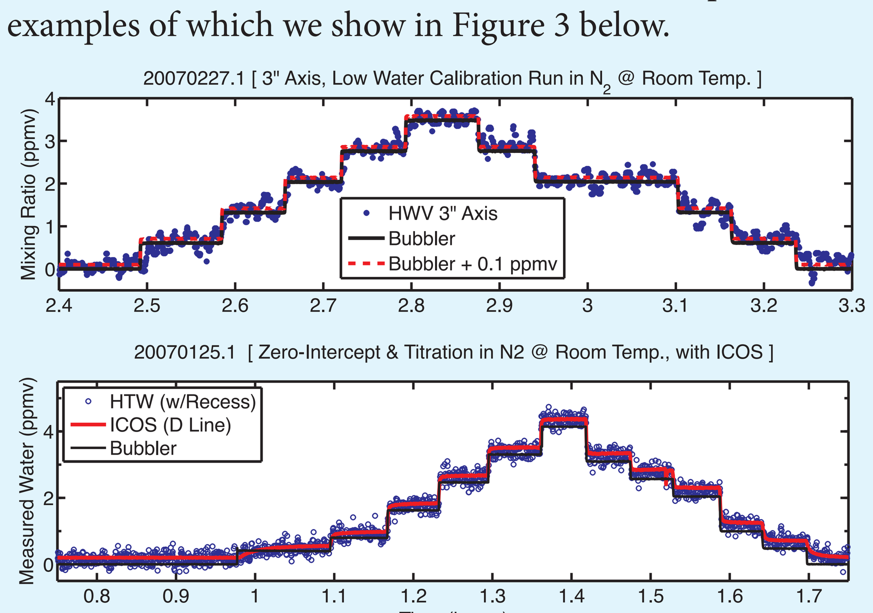

Figure 3. Low water vapor calibration runs for the ER2 (top panel) and WB57 total water (bottom panel) detection axes. For the ER2 axis, the plot of water vapor as determined by the water vapor addition system (bubbler) with 0.1 ppmv added illustrates the measured water vapor in the system prior to water being added and no measurable offset. A virtually identical background water vapor as measured by both the total water axis and the ICOS instrument is shown in the bottom panel.

CONCLUSION: Laboratory calibrations at low water vapor constrain any offset of the ER2 or WB57 Harvard Lyman α instruments to < 0.2 ppmv.

Because typical laboratory calibrations are carried out at room temperature, their insensitivity to temperature must be established. We show an example of the calibration's insensitivity to temperature in Figure 4.

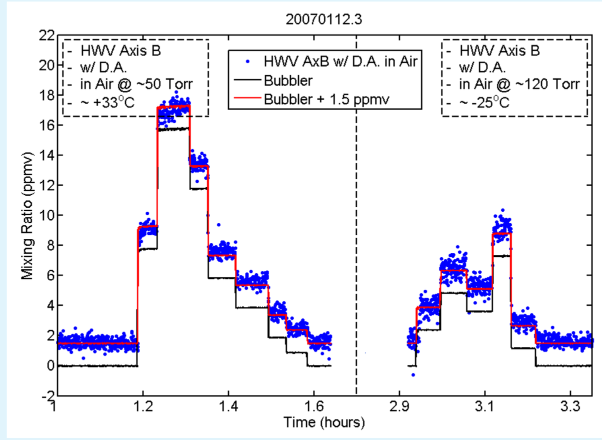

Figure 4. Repeat laboratory calibrations at temperatures 60°C apart illustrate temperature independence. All data are analyzed using the same calibration constants.

CONCLUSION: The temperature independence of laboratory calibrations carried out at atmospheric pressures Illustrates applicability of room-temperature calibrations to flight conditions.

Flight intercomparisons

AVE-WIIF July, 2005 Houston TX

In-flight validation of Harvard Lyman α during the AVE-WIIF mission is shown in Figure 5. We show data from six instruments but emphasize here agreement among all the Harvard instruments: four different instruments used three completely independent detection methods and four different sampling strategies. Agreement is demonstrated over a range of pressures, temperatures, and water vapor mixing ratios.

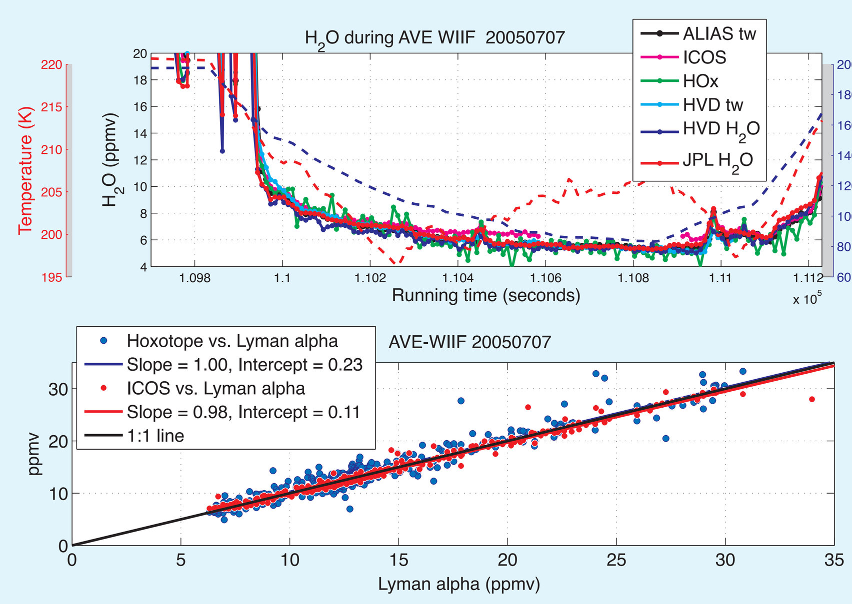

Figure 5. (TOP) Water vapor data taken during the last stratospheric segment of the 20050707 flight. Ambient pressure (dashed blue line) and temperature (dashed red line) are plotted as well.
(BOTTOM) Least squares fits to the raw data for the last AVE-WIIF flight where Hoxotope and ICOS are plotted respectively against Lyman α.

CONCLUSIONS: laboratory and in-flight agreement between Harvard water instruments validate Lyman alpha:

- Laboratory calibrations apply in flight.
- Offset constrained to at most 0.1 ppmv in nitrogen corresponding to 0.2 ppmv in air.

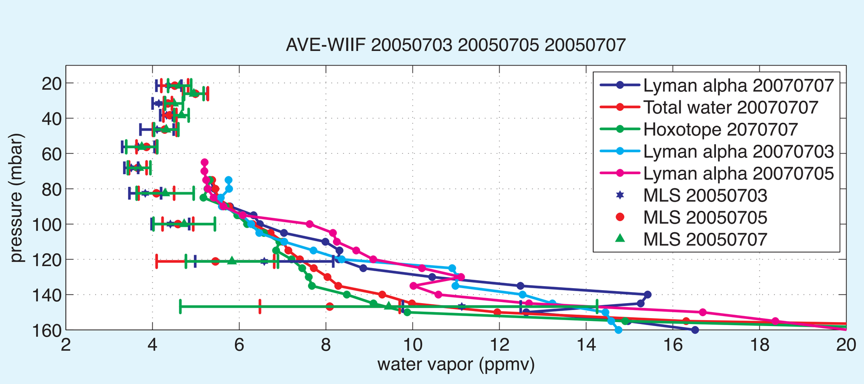

Figure 6. Intercomparison with MLS during Ave-WIIF.

CONCLUSION: Intercomparison of Harvard instruments with MLS illustrates systematic offset in UT/LS.

- In tropics MLS and CFH agree very well so MLS is surrogate for CFH during Ave-WIIF, and consistent with data in Figure 1.

CRAVE (Jan-Feb, 2006) and TC4 (August, 2007)

Differences consistent with these results were observed during the CRAVE and TC4 campaigns and included an intercomparison with MLS as shown in Figure 7.

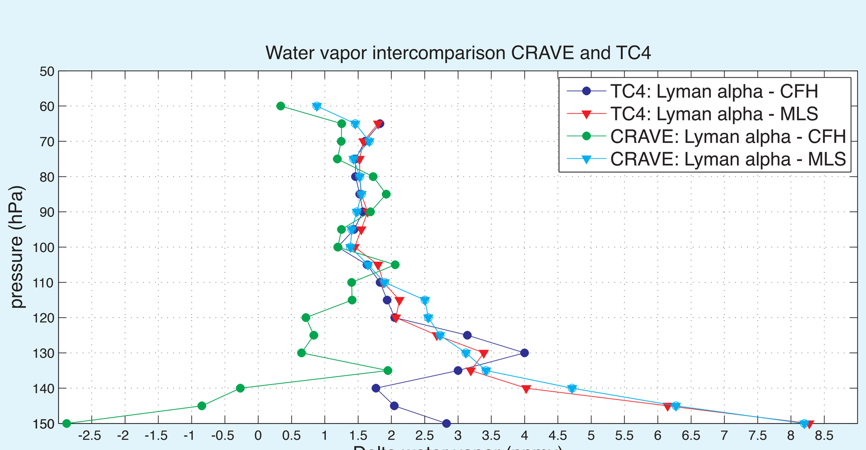

Figure 7. Intercomparisons between Harvard Lyman α and MLS and CFH during the CRAVE campaign and the TC4 mission, where the data are all binned and average at 5 hPa pressure intervals.

CONCLUSION: All intercomparison data between Harvard Lyman alpha and NOAA frost point instruments as well as MLS on the Aura satellite show a consistent difference of about 1.5 ppmv in the tropopause region and lower stratosphere.

So what can we learn from a carefully run laboratory intercomparison?

Recent AQUAVIT intercomparison

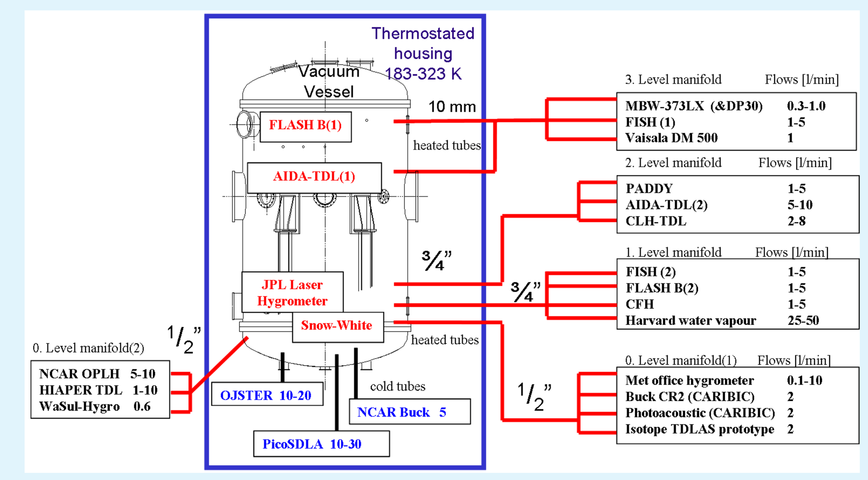

Figure 8. Instruments as configured during AquaVIT.

Key instrument of interest: Lyman α, CFH, JLH, FISH2, AIDA TDL, first four with extensive UT/LS data; last AIDA reference instrument.

Our approach:

1. Use analysis to distinguish between calibration errors (directly resolvable in lab), offsets or artifacts at low water, and sampling errors.

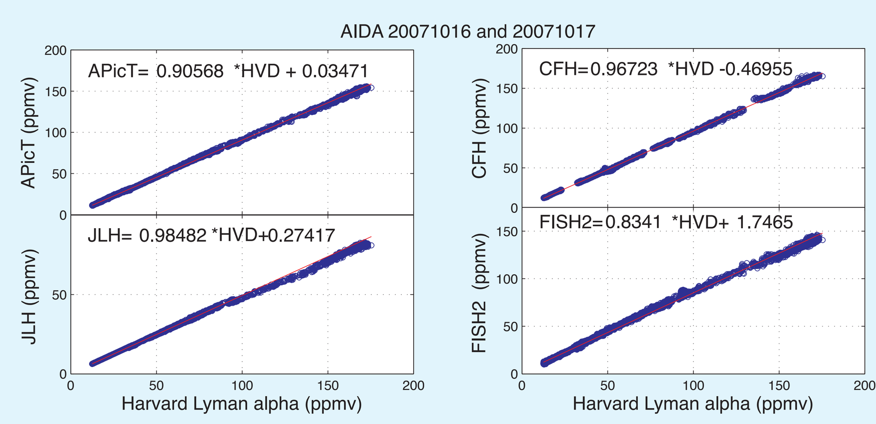

Figure 9. High water data on two days allows for calibration intercomparisons with Harvard Lyman α.

CONCLUSIONS:

- Agreement between Harvard, JLH and CFH is excellent; not quite as good between Harvard and AIDA TDL; still poorer between Harvard and FISH2.
- Large differences between HVD and FISH2 are resolvable in lab.

2. Examine low water results on 3 days while taking into account calibration differences. Magenta line represents modeled correction to Lyman α data because of insufficient flow.

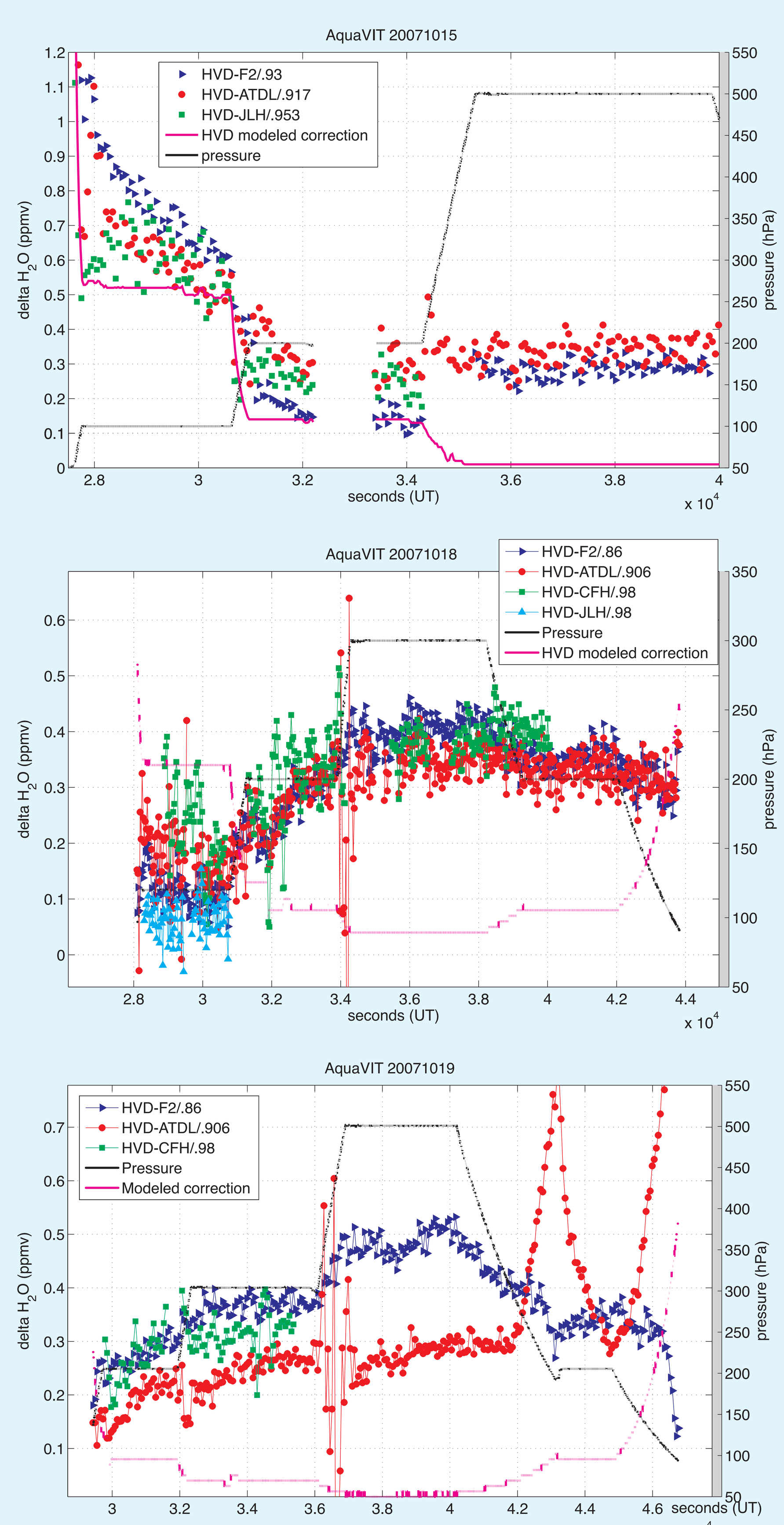

Figure 10. Low water data from the runs on the 15th, 18th, and 19th. The modeled correction is derived from diagnostic data taken as a function of flow and pressure.

CONCLUSIONS only from data where correction is negligible:

- Harvard Lyman α measures about 0.30±0.05 ppmv higher than the AIDA TDL
- Using the limited intercomparison data with CFH on the 18th and 19th, Lyman α is about 0.35±0.05 ppmv higher than CFH.
- The difference with JLH data is about 0.05-0.10 less than with AIDA TDL.
- The difference from Fish2 is slightly higher, about 0.40±0.10 ppmv.

MAJOR CONCLUSIONS from AquaVIT:

- Observed differences at low water are small, and do not approach those observed in-flight.
- Direct Laboratory intercomparisons under flight –equivalent conditions are needed for these instruments.

Using accurate water vapor measurements, what conclusions can we draw regarding the degree to which convective ice lofting and/or high supersaturations can affect the stratospheric water vapor budget?

Framework: Transform water vapor profiles in lower tropical stratosphere from potential temperature above the tropopause (390 K) to the date the sampled air mass crossed the tropopause using measured CO and a simple photochemical model, with CO_2 data used to validate the model [Weinstock *et al.*, 2001].

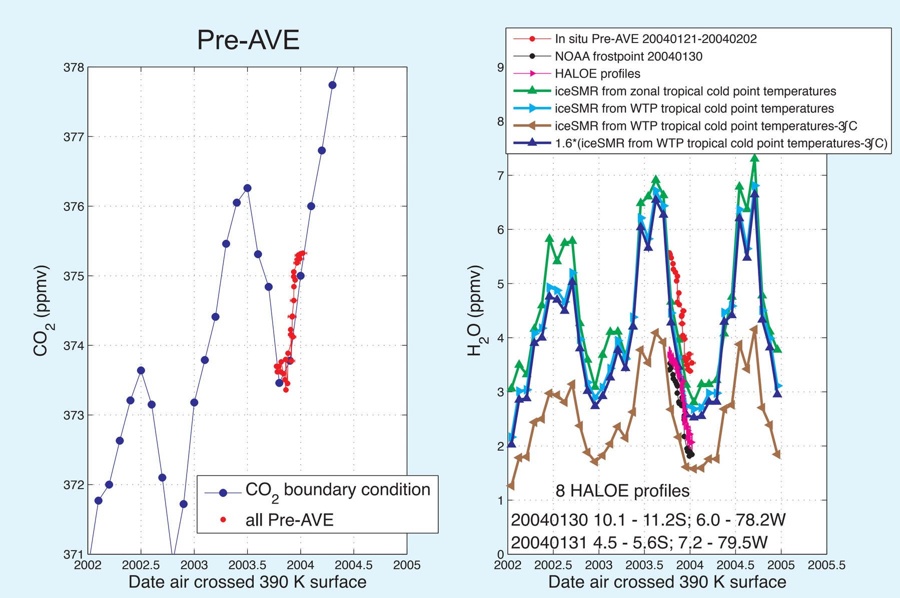

Figure 11. Mixing ratios measured above the tropopause plotted vs. the date that the sampled air mass crossed the 390 K isentrope: (a) carbon dioxide, and (b) water vapor. Included in panel (a) is a plot of $(CO_2)_{\rm d}$, boundary condition values. Included in panel (b) are profiles from frost point data plotted in Figure 1 as well as corrected HALOE profiles binned and averaged identically to the Harvard in situ data. For comparison to represent $(H_2O)_{\rm d}$ we plot ice saturation mixing ratios derived from monthly averaged radiosonde cold-point temperatures in the tropics. The blue line is derived from cold-point temperatures from 22 radiosonde stations that are distributed throughout the tropics. The cyan line is derived from data from nine stations in the western tropical Pacific (WTP). The 3-degree adjustment to the data from the WTP as described in the paper are provided to enable comparison with the work of Fueglistaler et al. [2004].

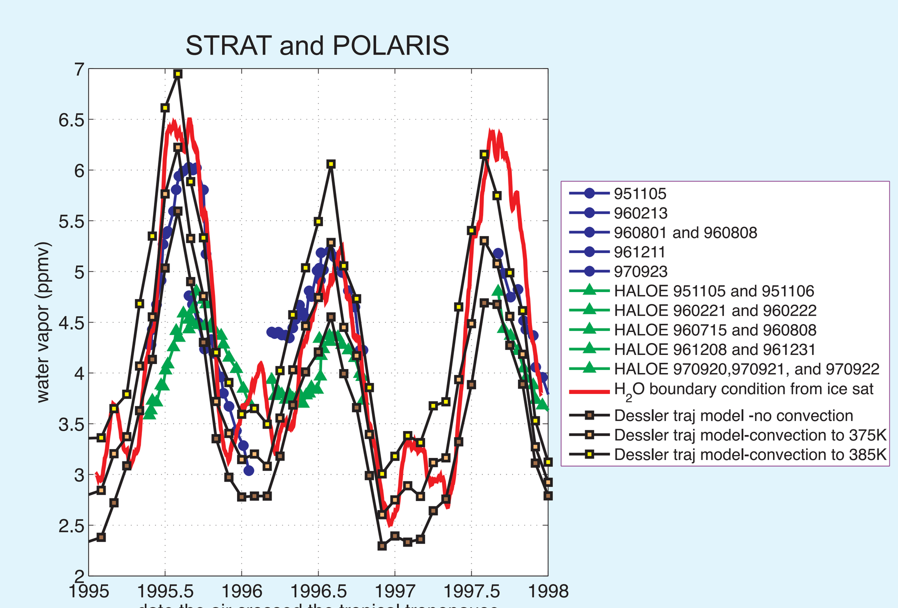

Figure 12. Comparison of the seasonal cycle of water vapor entering the lower tropical stratosphere derived from Harvard Lyman α and HALOE data and calculated from ice saturation at mean daily zonal tropical cold-point temperatures and from a Lagrangian trajectory model adapted by Dessler to include convection.

FINAL Conclusions:

Based on the accuracy of the Harvard Lyman alpha instrument we conclude:

1. Harvard in situ data during Pre-AVE are consistent with the ice saturation derived from Western tropical Pacific cold-point temperatures or from the Lagrangian model when air is dehydrated only to 1.6 rh. Alternatively, convection could play a role.
2. Harvard in situ data during the STRAT and POLARIS campaigns show that if air is dehydrated to the minimum ice saturation it experiences on its back trajectory, then convection to about 375K potential temperature is necessary to adequately moisten air entering the tropical stratosphere.